The fast spiral-in of the companion star to the black hole XTE J1118+480[1]

Jonay I. González Hernández[1,2], Rafael Rebolo[1,2,3], and Jorge Casares[1,2]

ABSTRACT

We report the detection of an orbital period decay of $\dot{P} = -1.83 \pm 0.66$ ms yr^{-1} in the black hole X-ray binary XTE J1118+480. This corresponds to a period change of -0.85 ± 0.30 μs per orbital cycle, which is ~ 150 times larger than expected from the emission of gravitational waves. These observations cannot be reproduced by conventional models of magnetic braking even when including significant mass loss from the system. The spiral-in of the star is either driven by magnetic braking under extremely high magnetic fields in the secondary star or by a currently unknown process, which will have an impact on the evolution and lifetime of black hole X-ray binaries.

Subject headings: black holes: physics — gravitation — stars: individual XTE J1118+480 — stars: magnetic field — X-rays: binaries

1. Introduction

Angular momentum loss (AML) in short-period black hole X-ray binaries are driven essentially by magnetic braking (Verbunt et al. 1981), gravitational radiation (Landau & Lifshitz 1962; Taylor & Weisberg 1982), and mass loss (Rappaport et al. 1982), with possible additional contributions from jets (King & Kolb 1999). Measurements of orbital period variations with time constrain the role of these processes in the evolution of such binaries (Verbunt 1993).

Magnetic braking is proposed as the main mechanism for AML in compact binaries (Rappaport et al. 1983). It produces the shrinking of the binary orbit and maintains the donor star in contact with its Roche lobe, therefore, sustaining stable mass transfer. Although this is an essential mechanism to understand compact binary evolution its actual prescription is currently debated and not well established (Ivanova 2006).

XTE J1118+480 is one of only 18 galactic X-ray binaries which contain a dynamical black hole (Casares 2007). With an orbital period of 4.1 hours it is the most compact black hole X-ray binary known. Determination of the times at the inferior conjunction of the ~ 0.2 M$_\odot$ secondary star with respect to the ~ 8 M$_\odot$ black hole have been obtained at different epochs since its discovery on UT 2000 March 29 by the Rossi X-ray Timing Explorer (Remillard et al. 2000). Previous attempts to estimate the orbital period derivative failed due to the small baseline of the observations (Johannsen 2009).

2. Observations

We have conducted new spectroscopic observations of XTE J1118+480 using the 10.4m Gran Telescopio Canarias (GTC) equipped with the OSIRIS spectrograph (Cepa et al. 2000, 2003) at the Observatorio del Roque de los Muchachos in La Palma (Canary Islands, Spain). Ninety seven medium-resolution spectra ($\lambda/\delta\lambda \sim 2,500$) were obtained on UT 2011 January 7, Febru-

[1]Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain; jonay@iac.es, rrl@iac.es, jorge.casares@iac.es

[2]Depto. Astrofísica, Universidad de La Laguna (ULL), E-38206 La Laguna, Tenerife, Spain

[3]Consejo Superior de Investigaciones Científicas, Spain

[1]Based on observations made with the Gran Telescopio Canarias (GTC), instaled in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofísica de Canarias, in the island of La Palma.

ary 8, and April 25–25, 36 and 36 spectra in each night respectively–. In Fig. 1 we display the radial velocities of the secondary star in its orbital motion around the center-of-mass of the system, derived using the cross-correlation technique with a template stellar spectrum properly broadened with a rotational velocity of $v \sin i = 100 \text{ km s}^{-1}$ (González Hernández et al. 2006, 2008). The radial velocity points, which spread over ~ 3 and a half months, provide a new determination of the current orbital period of $P_{\rm orb} = 0.16993379 \pm 0.00000047$ d, which is smaller although still consistent with the orbital period measurement previously determined on UT 2000 December 1 (Torres et al. 2004). In Table 1 we list these orbital period measurements, $P_{\rm orb}$, the updated dynamical masses of the black hole, $M_{\rm BH}$, and the secondary star, M_2, the mass ratio, q, the rotational velocity, $v \sin i$, the orbital inclination, i, the orbital semiamplitude velocity, k_2, the mass function, $f(M)$, the current radius of the secondary star, R_2, and orbital separation of the system components, a_c.

3. Orbital period decay

The spectroscopic data were used to derive three new times, T_n, of the inferior conjunction of the secondary star in this system (see Table 2). Assuming a constant rate of change of the orbital period, the time, T_n, of the nth orbital cycle can be expressed as $T_n = T_0 + P_0 n + \frac{1}{2} P_0 \dot{P} n^2$, where P_0 is the orbital period at time T_0 of the reference cycle ($n = 0$), $\dot{P}$ is the orbital period time derivative, and n, the orbital cycle number. We use the IDL routine CURVEFIT and obtain $T_0 = 2451868.8921 \pm 0.0002$ d, $P_0 = 0.16993404 \pm 0.00000005$ d, and a period derivative of $\dot{P} = -(5.8 \pm 2.1) \times 10^{-11}$ s/s with a reduced $\chi^2_\nu = 1.7$ with $\nu = 3$. A linear fit ($\dot{P} = 0$), and a third-order polynomial fit (including $\ddot{P}$), provide worse fits with $\chi^2_\nu = 2.9$ and 2.3, respectively. In Fig. 2 we have depicted the orbital phase shift, defined as $\phi_n = \frac{T_n - T_0}{P_0} - n$, of each of the T_n values as a function of the orbital cycle number n, together with the best-fit second-order solution. This figure shows a clear deviation from the null variation and that $\dot{P}$ is negative. Our result, which can be expressed as $\dot{P} = -1.83 \pm 0.66 \text{ ms yr}^{-1}$, represents the first determination of the orbital shrinkage in a low-mass black hole X-ray binary.
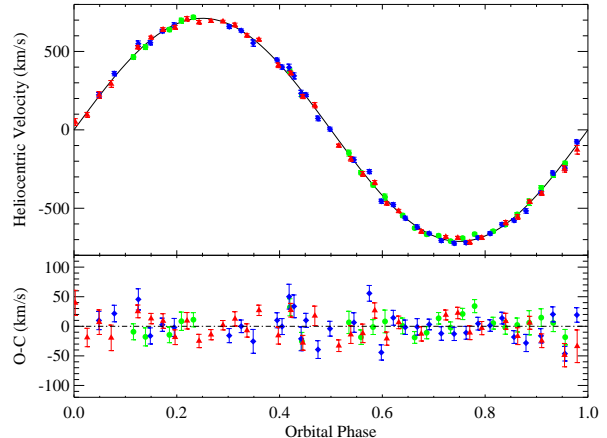

Fig. 1.— *Top panel*: radial velocities of the secondary star in the black hole X-ray binary XTE J1118+480 obtained from the GTC/OSIRIS spectroscopic data taken on the three nights of UT 2011 January 7 (green filled circles), UT 2011 February 8 (blue filled diamonds) and UT 2011 April 25 (red filled triangles), folded on the best-fitting orbital solution. *Bottom panel*: residuals of the fit, with a rms of $\sim 20 \text{km s}^{-1}$.
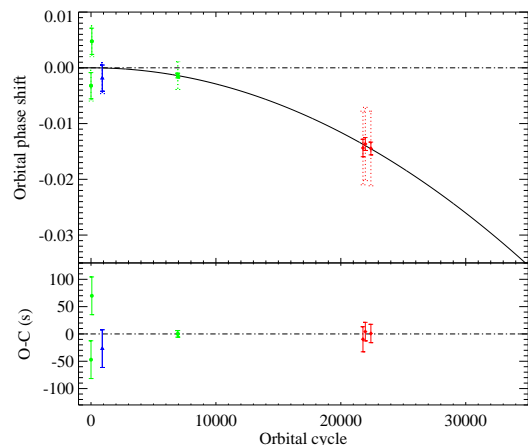

Fig. 2.— *Top panel*: orbital phase shift at the time of the inferior conjunction (orbital phase 0), T_n, of the secondary star in the low-mass black hole X-ray binary XTE J1118+480 versus the orbital cycle number, n, folded on the best-fit parabolic fit. Green filled circles are spectroscopic determinations, the blue filled triangle is a photometric measurement and red diamonds are the new GTC/OSIRIS spectroscopic determinations. Solid error bars show the uncertainties associated to the T_n determinations, whereas the dashed error bars also include the uncertainties associated to the T_0 and P_0 determinations. *Bottom panel*: residuals of the fit of the T_n values versus the cycle number n.

TABLE 1

KINEMATICAL AND DYNAMICAL BINARY PARAMETERS OF XTE J1118+480.

Parameter	Value	Reference
$v \sin i$	100^{+3}_{-11} km s^{-1}	[1]
i	68 ± 2	[2]
k_2	708.8 ± 1.4 km s^{-1}	[1]
$P_{\rm orb}$	$0.1699339(2)$ d	[3]
$P_{\rm orb}$	$0.1699338(5)$ d	[4]
$q = M_2/M_{\rm BH}$	0.027 ± 0.009	[1]
$f(M)$	6.27 ± 0.04 M$_\odot$	[1]
$M_{\rm BH}$	$8.30^{+0.28}_{-0.14}$ M$_\odot$	[4,5]
M_2	0.22 ± 0.07 M$_\odot$	[4,5]
R_2	$0.37^{+0.04}_{-0.05}$ R$_\odot$	[4,5]
a_c	$2.64^{+0.03}_{-0.02}$ R$_\odot$	[4,5]

NOTE.—References: [1] González Hernández et al. (2006); [2] Gelino et al. (2006); [3] Torres et al. (2004); [4] This work; [5] González Hernández et al. (2011)

4. Discussion and conclusions

General Relativity (Misner et al. 1973) predicts a secular periastron precession period of ~ 23 yr for XTE J1118+480. In the case of non-zero orbital eccentricity, this would affect the period inferred from succesive inferior conjunctions (see e.g. eq. 20 in Pál & Kocsis 2008). Using our data we set an upper-limit to the eccentricity of the black hole binary orbit of $e < 0.0067$ (95% confidence level), and conclude that relativistic periastron precession could only explain up to 50% of the measured orbital period decay.

The loss of energy through emission of quadrupole gravitational radiation, as predicted by general relativity, provides an orbital period derivative for this binary system of $\dot{P}_{\rm GR} \sim -0.01$ ms yr^{-1} (from eq. 8 in Taylor & Weisberg 1982) which is far below the observed rate of variation of the orbital period. On the other hand, the presence of jets in XTE J1118+480 has also been postulated based on X-ray and infrared observations (see e.g. Miller et al. 2002). However, the consequential AML due to jets even for relativistic jets (King & Kolb 1999) is ≤ 1000 times lower than the AML due to magnetic braking. The presence of a circumbinary disk is also proposed as possible AML mechanism in cataclysmic variables (see e.g. Taam et al. 2003), and the detection of mid-IR 4.5–8 μm excess emission (Muno & Mauerhan 2006) do support its existence in XTE J1118+480.

However, the estimated total mass of this disk is too small to affect the orbital angular momentum of this X-ray binary. Therefore, these effects cannot account for any significant additional contribution to the apparently too large orbital period decay measured in this black hole binary.

Most conventional magnetic braking and mass loss models for the binary parameters of XTE J1118+480 predict a much lower orbital period decay than we measure (see Fig. 3). Our observations appear inconsistent with these models. Only a very restrictive, rather unplausible subset of models, where nearly all the mass transferred by the secondary star is also lost by the system ($\beta = -\dot{M}_{\rm BH}/\dot{M}_2 \sim 0$), may lead to values of the orbital period derivative close to our observations (see Fig. 3).

Magnetic braking could be enhanced by anomalously high magnetic fields in the secondary star. We have estimated, from eq. 5 in Justham et al. (2006) and assuming that the mass lost by wind is equal to the mass transfer rate (derived from eq. 9 in King & Kolb (1999)), that a magnetic field at the surface of the companion star $B_s \geq 10 - 20$ kG is needed to explain the observations. The angular momentum loss due to magnetic braking is determined from eq. 9 in Johannsen et al. (2009). This magnetic field is 1–2 orders of magnitude larger than typical magnetic field strengths in highly-rotating low-mass stars (Phan-Bao et al. 2009). However, we cannot discard that the donor

N	$T_n - 2450000$ [a]	δT_n	Reference
0	1868.8916	0.0004	[1]
66	1880.1086	0.0004	[2]
904	2022.5122[b]	0.0004	[3]
6950	3049.93347	0.00007	[4]
21772	5568.6936	0.0003	[5]
21960	5600.6413	0.0002	[5]
22407	5676.6017	0.0002	[5]

[a]Time at inferior conjunction, T_n, of the secondary star in the low-mass black hole X-ray binary XTE J1118+480, and uncertainties, δT_n, corresponding to a given orbital cycle number, n.

[b]From photometric measurements.

NOTE.—References: [1] Wagner et al. (2001); [2] Torres et al. (2004); [3] Zurita et al. (2003); [4] González Hernández et al. (2008); [5] This work.
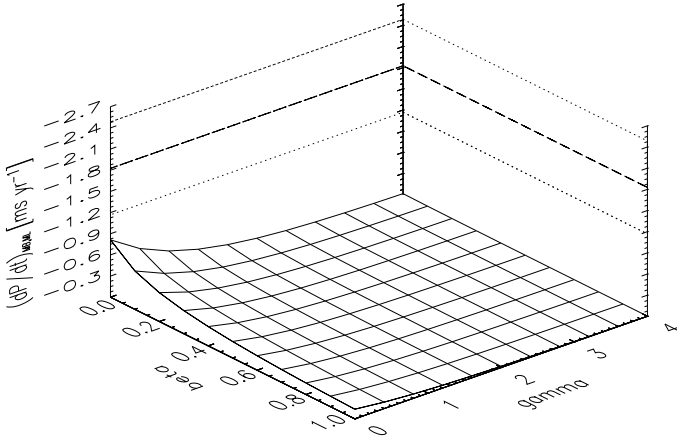

Fig. 3.— Theoretical estimate of the orbital period derivative in the low-mass X-ray black hole binary XTE J1118+480 due to magnetic braking and mass loss, $\dot{P}_{\mathrm{MB,ML}}$ given in ms/yr, derived from the second term of eq. 28 in Johannsen et al. (2009), as a function of two parameters: $\beta = -\dot{M}_{\mathrm{BH}}/\dot{M}_2$, the fraction of mass lost by the secondary star that is captured by the black hole; and γ, an index that characterizes the strength of the magnetic braking. The specific angular momentum, j_w, carried away by the mass lost from the system has been set to 1 which indicate that all the mass lost from the system is lost from the neighborhood of the black hole (or its accretion disk, see Podsiadlowski et al. 2002). Dashed lines represent the value derived from observations and the dotted lines, the values at 1-σ ver the uncertainty on the orbital period derivative, $\Delta\dot{P}$.

star in XTE J1118+480 descends from a magnetically peculiar Ap/Bp star that has retained most of its primordial magnetic field. In such stars very high magnetic fields of $\sim$ 20 kG have been observed (Elkin et al. 2010). Binaries with intermediate-mass Ap/Bp stars have indeed been postulated as the progenitors of compact black hole X-ray binaries (Justham et al. 2006). In particular, magnetically coupled, irradiation driven stellar winds can lead to substantial loss of systemic angular momentum (Justham et al. 2006) required to form low-mass X-ray binaries out from intermediate-mass binaries (Podsiadlowski et al. 2002). The detection of CNO-processed material in XTE J1118+480 strongly suggests that the donor descends from an intermediate-mass star (Haswell et al. 2002). Our discovery of a large period decay in XTE J1118+480 is also consistent with this scenario although we cannot rule out the possibility that other mechanism, not yet identified, plays a major role in the loss of angular momentum and hence the evolution of black hole X-ray binaries. In any case, our observations suggests a faster evolution and shorter lifetimes than previously assumed. This would help to reconcile the population number of low-mass X-ray binaries and millisecond pulsars, a long-standing problem in galactic astronomy (Podsiadlowski et al. 2002). Follow-up spectroscopy in the coming years may provide a determination of the second derivative of the orbital period with strong implications on our knowledge on the formation and evolution of black hole X-ray binaries.

The black hole in XTE J1118+480 was possibly formed in a violent supernova explosion that

launched the system via an asymmetric natal kick (Gualandris et al. 2005) from its formation region in the Galactic thin disk (González Hernández et al. 2006) to its present location in the Galactic halo (Mirabel et al. 2001). A lower limit to the age of the system of ≥ 11 Myr was derived from its peculiar location and kinematics. This limit has been used to set constraints on the rate at which black holes can evaporate in the Anti-de Sitter (AdS) braneworld Randall-Sundrum gravity model (for details see the introduction in Johannsen et al. 2009; Johannsen 2009) via the emission of a large number of conformal field theory (CFT) modes (Emparan et al. 2003).

An upper-limit to the asymptotic AdS curvature radius in the extra dimensions was established at $L \leq 80\ \mu m$ (Psaltis 2007), restricting deviations from the gravitational inverse square law to manifest only at distances smaller than L.

The orbital period evolution in this system was studied before but with a less number of measurements of T_n spread in a shorter interval of time, thus providing a period derivative consistent with zero at 1-σ (Johannsen 2009), and an upper-limit of $L \leq 97\ \mu m$. In their eq. 2, these authors assumed no angular momentum loss due to mass lost from the system ($j_w = 0$), no accretion onto the black hole ($\beta = 0$), and the parameter γ, which governs the strength of magnetic braking, equal to zero (see also Fig. 1 in Johannsen 2009). If we adopt the black hole and secondary masses given in Table 1, our determination of the orbital period decay provides a much tighter constraint on the asymptotic AdS curvature radius of $L \leq 35\ \mu m$ at 2-σ. This limit is more restricted than the best current table-top experiment upper-limit of $L \leq 44\ \mu m$ (Kapner et al. 2007). We note here that the size of the extra dimensions has been also recently constrained from the age of a black hole in a extragalactic globular cluster, placing an upper-limit as low as $L \leq 3\ \mu m$ (see Gnedin et al. 2009).

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